Thermal performances of nanoscale-gap thermophotovoltaic energy conversion devices

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The thermal effects on the performances of $In_{0.18}Ga_{0.82}Sb$ based nanoscale-gap thermophotovoltaic (nano-TPV) energy conversion devices are analyzed via the solution of the coupled near-field thermal radiation, charge and heat transport problem. The results suggest that the performances are quite low due to excessive heating of the p-n junction converting radiation into electricity. This problem could be circumvented by designing nanostructures selectively emitting thermal radiation in the near-field.

INTRODUCTION

In thermophotovoltaic (TPV) energy conversion, a heat source is employed to maintain a radiator at a specified temperature, which in turns emits thermal radiation toward a cell generating electricity. In order to potentially improve the power output and conversion efficiency of TPV systems, Whale and Cravalho [1] proposed to separate the radiator and TPV cells by a sub-wavelength vacuum gap. At sub-wavelength distances, radiation heat transfer is in the near-field regime, such that the energy exchanges can exceed the values predicted for blackbodies. For thermal radiation temperatures, the near-field effects become dominant when the bodies are separated by few tens of nanometers. Therefore, a TPV system using the near-field effects of thermal radiation is referred hereafter as a nanoscale-gap TPV (nano-TPV) device. While the studies available in the literature have clearly shown that the near-field effects of thermal radiation can substantially improve the electrical power output of TPV systems [1-3], some important questions about the feasibility of nano-TPV energy conversion are still unanswered. In this work, we aim to study the energy required for maintaining the TPV cells at room temperature via the analysis of the thermal effects in nano-TPV devices. For purpose of comparison with the literature, we study systems based on $In_{0.18}Ga_{0.82}Sb$ cells [3].

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EVALUATION OF NANO-TPV SYSTEM PERFORMANCES

As shown in Fig. 1, a bulk radiator (tungsten W, T_0 = 2000 K) and a TPV cell ($In_{0.18}Ga_{0.82}Sb$, bandgap E_g of 0.56 eV at 300 K) are separated by a sub-wavelength vacuum gap of length d_c. The TPV cell consists of a single p-n junction, where the thicknesses of the p-doped and n-doped regions are given by t_p = 0.4 μm and t_n = 10 μm [3]. As the TPV cell is likely to heat up from various sources (absorption by the free carriers and the lattice, non-radiative recombination and thermalization [4]), a thermal management system is used to maintain the p-n junction around room temperature. The cooling system is modeled as a convective boundary with a fixed temperature T_∞ = 293 K and a heat transfer coefficient h_∞.

The performances of the nano-TPV device are evaluated through the solution of the coupled near-field thermal radiation, charge and heat transport problem. The mathematical details as well as the modeling of the optical, electrical and thermophysical properties are given in reference [4].

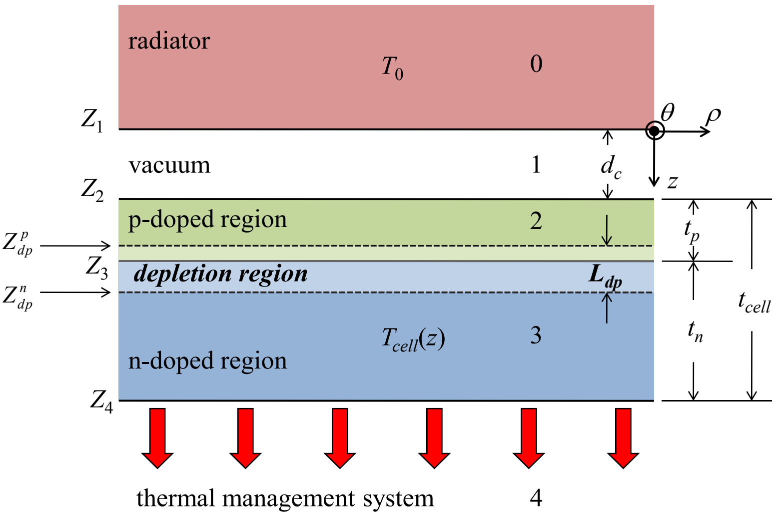
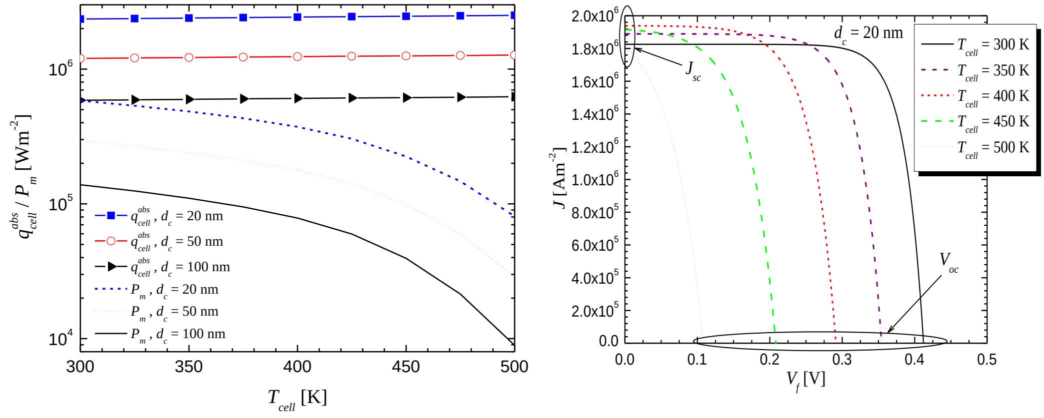


Figure 1. Schematic representation of the nano-TPV power generation system under study.

When the temperature of the cell is varied artificially (i.e., the energy equation is not solved), it can be observed in Fig. 2(a) that thermal radiation absorption increases slightly as the temperature of the cell increases mostly due to the fact that E_g decreases. On the other hand, the electrical power output P_m decreases significantly when T_{cell} increases, regardless of the gap d_c. For example, the conversion efficiency η_c is 24.8% when d_c = 20 nm and T_{cell} = 300 K, a value that drops to 3.23% when T_{cell} = 500 K.

Figure 2(b) shows that the short-circuit current J_{sc} slightly varies with T_{cell}, while the open-circuit voltage V_{oc} significantly decreases with increasing T_{cell} (due to an increasing dark current), thus explaining the low P_m and η_c values reported above.



(a) (b)

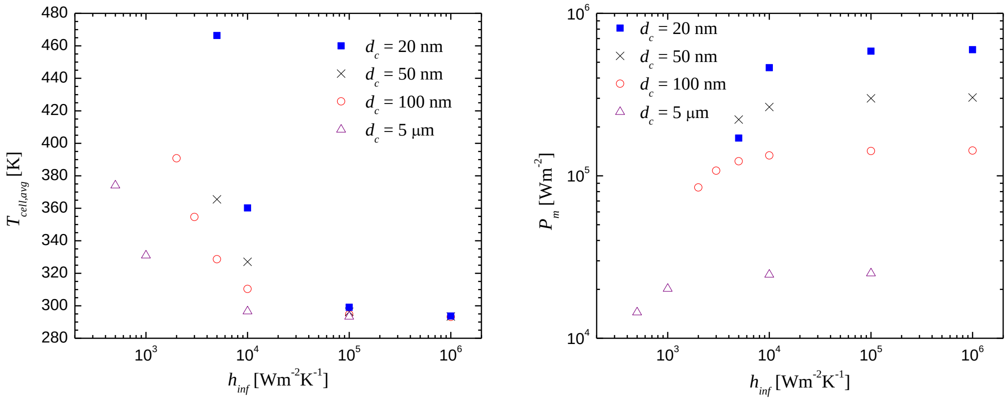
Figure 2. (a) Radiation absorbed by the cell and electrical power output as a function of T_{cell} and d_c. (b) *J-V* characteristic for d_c = 20 nm as a function of T_{cell}.

Figure 3(a) shows averaged cell temperature $T_{cell,avg}$ as a function of the heat transfer coefficient h_∞ for various gaps d_c. The values of h_∞ needed to maintain the TPV cell around 300 K are quite high. Indeed, for a gap d_c of 5 μm, a h_∞ value of 10^4 Wm^{-2}K^{-1} is required to maintain the p-n junction around room temperature, while a h_∞ of 10^5 Wm^{-2}K^{-1} is needed for gaps d_c of 100 nm, 50 nm, and 20 nm. Generally speaking, heat transfer coefficients h_∞ up to 10^3 Wm^{-2}K^{-1} can be achieved via free convection, while h_∞ up to about 2×10^4 Wm^{-2}K^{-1} can be reached by forced convection; heat transfer coefficients above this threshold are possible via convection involving phase change. The results of Fig. 3(a) should not be surprising, since radiation with energy E exceeding the bandgap E_g largely contributes to heat generation in the p-n junction. The use of a bulk radiator in the near-field provides a broadband enhancement of the flux, which contributes simultaneously to increase the electrical power output and to increase heat generation within the p-n junction.

The electrical power output is presented in Fig. 3(b) as a function of d_c and the heat transfer coefficient h_∞. As expected, the performances of the nano-TPV devices are significantly affected by the thermal boundary condition imposed at Z_4. For example, when d_c = 20 nm, the conversion efficiency η_c is 25.4% when $h_\infty = 10^6$ Wm^{-2}K^{-1} ($T_{cell,avg}$ = 294 K), and this value drops to 6.9% when $h_\infty = 5\times10^3$ Wm^{-2}K^{-1} ($T_{cell,avg}$ = 466 K).

CONCLUSIONS

The results presented in this work suggest that the performances of the nano-TPV devices proposed so far in the literature are quite low. A potential way to avoid excessive heating of the cell is to design nanostructures selectively emitting thermal radiation in the near field. The performance of the nano-TPV device discussed here could be analyzed further as a function of the doping levels, the configuration of the cell, the thicknesses of the p- and n-doped regions, and the relative proportion of GaSb and InSb. Finally, the impacts of using radiators made of thin films of W should be investigated in a future research effort.



(a) (b)

Figure 3. (a) Averaged cell temperature $T_{cell,avg}$ as a function of d_c and h_∞. (b) Electrical power output P_m as a function of d_c and h_∞.

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